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Invited Review

Carbon-constrained firm decisions: From business strategies to operations modeling

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ABSTRACT

This paper presents a systematic literature review on carbon-constrained operations models. First, carbon constraints are defined and categorized into three genres: policy-driven, market-driven, and nature-driven. Second, business strategies for fulfilling carbon constraints are summarized and classified into three main groups: internal emissions abatement, collaborative emissions abatement, and carbon compensation. Subsequently, ten specific types of carbon-constrained operations models are studied in support of these business strategies. Lastly, the research trend is analyzed and a conceptual studying framework is proposed. The results show that the policy-driven carbon constraints are the primary carbon considerations in operations models, with the emissions trading scheme and the carbon tax taking first and second place, respectively. In addition, the focus of carbon-constrained operations models evolves from short-term to long-term strategies, from internal to collaborative abatement strategies, and from simple to more practical models. From the carbon constraint modeling perspective, future studies regarding the coexistence of multiple carbon constraints and their interactive effects might have interesting results. From the business strategy perspective, the collaborative emissions abatement models, especially horizontal co-opetition mechanisms, remain to be further explored.

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1. Introduction

In the past decade, climate change issues have received increased attention worldwide. Scientific evidence proves that anthropogenic greenhouse gases (GHG) such as carbon dioxide emissions are the main cause of climate change (IPCC, 2014). The ratification of the 2015 Paris Agreement indicates the concerted aspiration of countries around the world to reduce CO_2 emissions and mitigate climate change. Although U.S. President Donald Trump left the Paris Agreement, the U.S. Climate Action Pavilion was set up with the support of the Bloomberg Philanthropies at the last UNFCCC Conference of the Parties (COP23) in Bonn, Germany, on November 2017 to announce the "American's Pledge" that "across America, states, cities, businesses, universities, and citizens are taking action to fight climate change".[1]

A notable fact is that nearly two-thirds of historical GHG emissions are attributed to only 90 entities, including both state-owned and investor-owned firms (Heede, 2014). Leading carbon emissions producers are experiencing pressure from government regulations, market demand for low-carbon products, and other responsibilities as requested by stakeholders. When first confronted with the emerging carbon constraints, many firms resisted changing and disputed the environmental and economic aspects; while later on firms gradually begin taking proactive actions towards emissions reduction (Kolk & Pinkse, 2005; Jeswani, 2008). Managing climate change proactively is now not only an action for corporate responsibility but also a business strategy to gain a potential competitive advantage (Porter & Reinhardt, 2007; Haddock-Fraser & Tourelle, 2010; Lash & Wellington, 2007). Therefore, it is important, even fundamental, for firms to design low-carbon business strategies and adjust operational decisions to work within the carbon-constrained business environment.

Since the early 2000s, interest in sustainable operations in academic literature has been growing (see, e.g., Kleindorfer, Singhal, & Van Wassenhove, 2005; Drake & Spinler, 2013; Lee & Tang, 2018), especially from an environmental perspective (Corbett & Klassen, 2006). Scholars such as Linton, Klassen, and Jayaraman (2007), Sarkis, Zhu, and Lai (2011), Tang and Zhou (2012), and Seuring and Müller (2008) have conducted comprehensive literature reviews on topics including environmentally and socially sustainable operations, green supply chains, and sustainable supply

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[1] More details can be found in the webpage: https://www.americaspledgeonclimate.com/

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chains. While carbon constraints may share some common features with environmental constraints, they differ in several aspects. First, climate change is a global issue rather than a local or regional issue. Second, carbon emissions reductions may not only reduce environmental externalities but also lower operations costs through more efficient energy consumption and transportation (Hoffman, 2005). Third, innovative policy instruments, such as the emissions trading scheme, are implemented to control carbon emissions on either regional or national levels for various industries. These characteristics have caused many scholars to focus explicitly on carbon-constrained operations management. According to Plambeck (2012), academic literature explicitly addressing carbon-constrained operations management has a promising future, but it is still in its nascent period. Tiwari, Chang, and Choudhary (2015) summarize 25 articles published in the special issue "Carbon-efficient production, supply chains and logistics" of the *International Journal of Production Economics*. Memari, Rahim, Ahmad, and Hassan (2016) review 31 journal articles on the green supply chain and logistics that focused on planning and controlling supply chain activities with respect to CO_2 emissions. However, a systematic review of the studies on carbon-constrained operations models is still lacking, especially considering the rapidly growing number of studies in this area. This paper provides a conceptual analyzing framework for studying firms' carbon-constrained operations decisions through a systematic literature review and proposes potential research directions in this area.

In this study, carbon constraints are defined and categorized into three groups: policy-driven, market-driven, and nature-driven. Policy-driven constraints refer to the regulatory disciplines acting on firms, which may be imposed by either the outer institutions such as governments or the firms' inner managing boards. Market-driven constraints refer to concerns from the product market environment, which may include the consumers' preference towards low-carbon products, low-carbon quality competition with competitors, and other stakeholder requirements. Nature-driven constraints refer to the physical risks from climate changes in the natural system, which may have strong impacts on regular business. Possible business strategies for fulfilling the carbon constraints, including internal emissions abatement, collaborative emissions abatement, and carbon compensation, were then analyzed and attributed to the three categories. Ten types of carbon-constrained operations models from 116 journal articles are studied in support of the categorized business strategies. Next, the modeling methodologies are summarized and a conceptual analyzing framework is constructed, which consists of recognizing carbon constraints, selecting business strategies, modeling and making operations decisions. The developing trend of carbon-constrained operations models is analyzed with potential directions for future research. The results show that the policy-driven carbon constraints are the primary carbon considerations in the existing operations models, with the emissions trading scheme and the carbon tax taking first and second place, respectively. Furthermore, the focus of carbon-constrained operations models evolves from short-term to long-term strategies, from internal to collaborative abatement strategies, and from simple to more practical models. From the carbon constraint modeling perspective, future studies of the coexistence of multiple carbon constraints and their interactive effects might provide interesting results. From the business strategy perspective, the collaborative emissions abatement models, especially cooperation mechanisms of competitive firms, would require further study.

The remainder of this paper is organized as follows: Section 2 describes the definition and categorization of carbon constraints. Section 3 summarizes possible carbon-constrained business strategies. Section 4 is a systematic review of 116 journal articles on carbon-constrained operations models in support of the categorized business strategies. Section 5 analyzes the research trend and presents a conceptual analyzing framework. Section 6 concludes the paper with potential research directions for future study.

2. Carbon constraints

Terms such as "carbon constraints", "carbon pressures" and "climate concerns" are frequently used in literature. However, the explicit definition of carbon constraints is seldom given. From a corporate risk management perspective, Busch and Hoffmann (2007) define carbon constraints as all sorts of conditions that focus on carbon issues and limit firms in their way of conducting business and in their efforts towards profitability. Busch and Hoffmann also categorize the carbon constraints as either input dimension (related to fossil fuel issues) or output dimension (related to climate change issues). This paper focuses on the output dimension, which relates to climate change issues caused by carbon emissions. The definition of carbon constraints in this regard is given as follows:

Definition 1. Carbon constraints are conditions concerning carbon emissions that may influence firms' business strategies, operations decisions, and profitability.

After examining the relevant literature, we categorize the defined carbon constraints into three groups: policy-driven constraints, market-driven constraints, and nature-driven constraints. This categorization enables us to find appropriate modeling methods after recognizing a specific carbon constraint in practice. Table 1 shows the detailed carbon constraints mentioned in business literature in each category, with the emissions trading scheme (ETS) and consumer preference being the most frequently mentioned carbon constraints. In the following subsections, each genre of carbon constraints will be explained in detail.

Table 1
Categorization of carbon constraints discussed in the business literature.

Study	Policy-driven				Market-driven		Nature-driven
	Cap	Tax	ETS	Offset	Consumer preference	Other stakeholder pressures	Physical risks
Hoffman (2005)	√		√	√	√	√	
Schultz and William-son (2005)	√	√	√		√		√
Busch and Hoff-mann (2007)		√	√		√	√	√
Lash and Welling-ton (2007)	√		√	√	√	√	√
Jeswani et al. (2008)			√	√	√	√	
Haddock-Fraser and Tourelle (2010)	√				√	√	
Sprengel and Busch (2011)		√	√		√	√	
Böttcher and Müller (2015)	√		√		√	√	
Sakhel (2017)	√	√	√		√		√
Tsalis and Nikolaou (2017)	√	√	√	√	√	√	√

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2.1. Policy-driven constraints

Policy-driven carbon constraints refer to regulatory policies and measures imposed on firms by governments, shareholders, or managers to control carbon emissions. Climate change policy tools can be classified into two categories: mandatory and non-mandatory. Mandatory policy tools are strict guidelines imposed on firms. This type of carbon control policy usually consists of three formats: (1) place a strict total emissions cap on a firm or facility for a certain planning period; (2) release the carbon intensity standard for a certain type of product; and (3) require the use of specific technologies for a firm's production or operational activities. In practice, governments or managers often set targets for emissions reduction percentages (e.g., China's 'five-year plan' and Walmart's emissions abatement initiatives), which actually represents the first format, i.e., setting emissions caps that are calculated by using historical emissions and reduction rate targets. Although the second format is currently hard to implement due to the challenge in emissions accounting, it has been studied in the modeling literature. The third format is also frequently used in practice (e.g., governments may require power plants to generate a minimum percentage of renewable electricity).

Non-mandatory policy tools are more flexible than mandatory ones and are usually based on market laws that allow firms to choose between reducing and paying for emissions. The implemented non-mandatory policy tools include cap-and-trade (also known as emissions trading scheme or ETS), tax, cap-and-offset, and subsidies/penalties for positive/negative behaviors. Among these various tools, increasing attention has been focused on the ETS by both researchers and practitioners (e.g., EU's ETS, China's National ETS, and California's ETS). Under this policy, initial emissions permits (or caps) are allocated to firms for a given planning horizon (Zhou & Wang, 2016). If a firm's actual emissions level exceeds the cap, it must purchase additional carbon emissions allowances from the trading market to cover its excess. However, if a firm's actual emissions level is lower than the cap, it may sell its surplus allowances in the trading market. The cap-and-offset policy tool is similar, but different, from the ETS. Under this policy, initial emissions caps are also allocated to firms. These firms may purchase additional carbon credits from certified emissions reduction sources if their emissions levels exceed the caps. However, if a firm's emissions level is below the cap, it cannot sell the surplus. The first cap-and-offset mechanism designed for implementation is the Clean Development Mechanism (CDM) proposed in the Tokyo Protocol. Some countries, such as France, Japan, and Chile, use the carbon tax to charge a fixed price for each unit of carbon emissions. In addition to these three frequently adopted tools, governments may also use complementary tools, such as subsidizing low-carbon technologies (e.g., renewable energies or electric cars), and punishing rule-breakers with penalties or public criticism.

2.2. Market-driven constraints

Market-driven carbon constraints are carbon concerns arising from the product markets. Consumer preference towards low-carbon products is a fundamental component of market-driven carbon constraints. Empirical evidences show that consumers are becoming increasingly concerned with the environmental impacts of manufacturers; therefore, purchasing decisions are more likely to be based on the carbon footprints embodied in the products (Li & Veld, 2015; Shuai, Ding, Zhang, Guo, & Shuai, 2014). Consequently, the shift in consumer preference affects product sales and influences profit margins. In addition, firms are being challenged by their competitors in low-carbon operations management, which may create competitiveness in many areas. Emissions reduction activities may result in cost reductions through improved energy efficiency, freight schedule, or other operational processes (Hoffman, 2005). Lower carbon emissions may form a brand image and bring environmental quality competitiveness to a firm, which often leads to higher prices and larger market shares as compared with its competitors (Amacher, Koskela, & Ollikainen, 2004). Moreover, firms are also exposed to other stakeholder pressures, including investors' low-carbon performance evaluation, non-governmental organizations' requirements, social media publicity, and employees' perception (Sprengel & Busch, 2011).

2.3. Nature-driven constraints

In addition to policy-driven and market-driven carbon constraints, firms may also encounter potential physical risks from climate changes in the natural system, such as rising sea levels, extreme weather, droughts, or floods. We name this type of potential risk nature-driven carbon constraints, which may influence the business environment and therefore affect firms' operations decisions (Busch & Hoffmann, 2007; Sakhel, 2017). For instance, extreme weather, such as long-lasting storms, may interrupt the transportation systems supporting business activities, while irregular precipitation may affect the growth of crops and other commercial plants. Therefore, firms need to prepare to adapt to the changing physical and societal environments.

3. Carbon-constrained business strategies

Firms may create strategies to work with the above-mentioned carbon constraints. Table 2 lists several terminologies and categorizations used in previous studies for describing such strategies. By consolidating the existing definitions and categories, we derive the definition of carbon-constrained business strategies as presented in Definition 2.

Definition 2. Carbon-constrained business strategies are strategic options for firms to adopt regarding the carbon constraints in Definition 1, which can be categorized into three main genres: internal carbon emissions abatement, collaborative carbon emissions abatement, and carbon emissions compensation.

Fig. 1 shows the proposed framework of carbon-constrained business strategies. Note that we exclude carbon accounting and reporting strategies from our framework and focus on firms' operations countermeasures, as we presume that the realization of actual carbon emissions is not an issue. For a detailed review of carbon accounting, please refer to Stechemesser and Guenther (2012).

3.1. Internal carbon emissions abatement

With regard to carbon constraints, firms could choose to reduce carbon emissions on their own, which is known as the internal carbon emissions abatement strategy. Primarily, firms may use the following three ways for internal emissions abatement.

(1) *Output reduction.* Reducing production output is a rapid, but unsustainable, method to reduce a firm's total carbon emissions, especially for carbon-intensive products such as cement, steel, and electricity. For example, in order to achieve clear "APEC Blue" skies for the APEC summit in 2014, approximately 10,000 factories in the regions surrounding Beijing suspended production (Huang, Zhang, & Lin, 2015). By using this strategy, a firm could satisfy policy regulations for total carbon emissions without making additional investments in low-carbon technologies or greener facilities. However, it is considered to be an inefficient short-term compliance strategy because it may decrease profit and compress consumer surplus, which enlarges the deadweight loss of social welfare. This strategy is not effective for market-driven

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Table 2
Terminologies and categorizations of business strategies concerning carbon emissions.

Study	Terminology	Categorization
Kolk and Pinkse (2005)	Business responses to climate change	Innovation vs compensation, internal vs vertical supply chain vs horizontal measures
Weinhofer and Hoffmann (2010)	Corporate CO_2 strategy	CO_2 compensation, CO_2 reduction, Carbon independence
Lee (2012)	Corporate carbon strategy	Reduction commitment, product development, process improvement, new market development, organizational involvement, external relationship development
Kroes et al. (2012)	Operational carbon compliance levers	At-source pollution prevention, end-of-pipe pollution control, use of allowances
Böttcher and Müller (2015)	Low-carbon operations management	Low-carbon products, low-carbon production, low-carbon logistics
Cadez and Czerny (2016)	Climate change mitigation strategies	Internal carbon reduction, external carbon reduction, carbon compensation
Lee and Klassen (2016)	Carbon management practices	Intra-organizational practices, inter-organizational practices

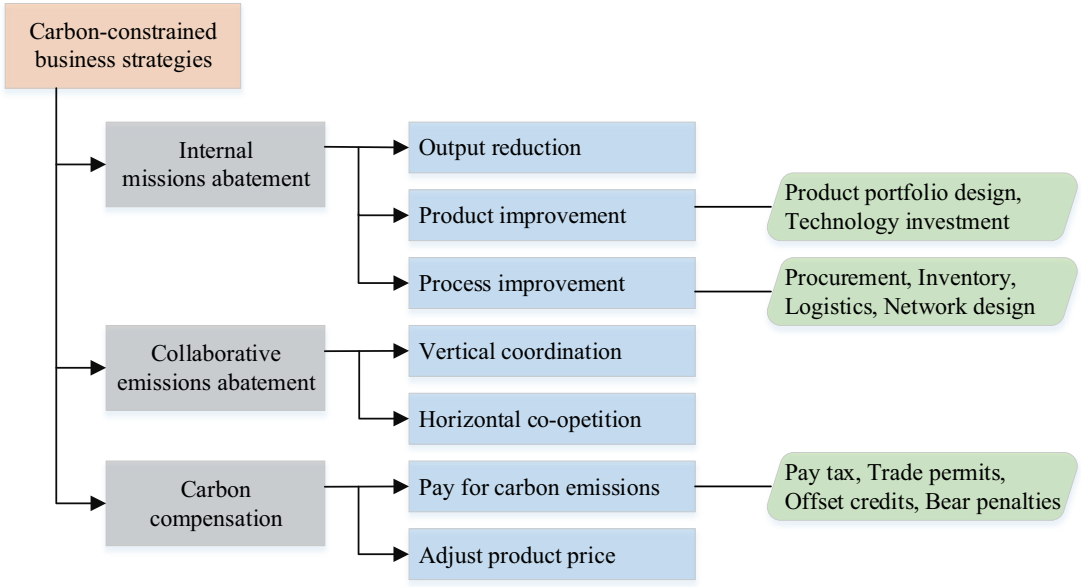

Fig. 1. Framework of carbon-constrained business strategies.

carbon constraints as it does not reduce a product's carbon intensity, or more explicitly, it does not improve the product's environmental (low-carbon) quality.

(2) *Product improvement.* Instead of reducing production quantity, a firm could also reduce its carbon emissions by lowering the emissions intensity of its product (the carbon emissions generated from the production of unit product). Methods used to achieve this goal include adopting green production technologies (Drake, Kleindorfer, & Van Wassenhove, 2016), switching to cleaner energies or input materials such as renewables (Kök, Shang, & Yücel, 2018), investing in end-of-pipe carbon emissions abatement technologies such as carbon capture and storage (İşlegen & Reichelstein, 2011), and redesigning product portfolios (Gong & Zhou, 2013). This would allow a firm to address both policy-driven and market-driven carbon constraints simultaneously. However, product improvement is often achieved through additional investments or higher operating expenditures. There must be a compromise between low-carbon product development and low-cost operations; firms need to perform a careful analysis to evaluate the costs and benefits when choosing this strategy.

(3) *Process improvement.* In addition to output reduction and the direct investment in low-carbon production, a firm may also achieve carbon emissions abatement goals through process improvements such as procurement, inventory and distribution. For instance, changing from offshore to onshore procurement may significantly reduce the carbon emissions generated from product transportation (Sunar & Plambeck, 2016); placing larger orders with less frequency may reduce potential freight emissions (Benjaafar, Li, & Daskin, 2013); and designing an efficient supply chain network may keep carbon emissions and operating costs relatively low (Cachon, 2014). Additional investments are not necessary for this strategy, which makes profitable carbon emissions abatement possible. However, when implementing this strategy, other supply chain issues must be considered, such as lead times, response requirements, supplier availability, and consumer preferences. Elaborate operational models and algorithms are the prerequisites for making appropriate decisions with this strategy.

3.2. Collaborative carbon emissions abatement

In addition to internal emissions abatement, a firm may also collaborate with its supply chain partners or even competitors to achieve emissions reduction targets (Zhang & Wang, 2014). This is especially useful when a joint emissions reduction pattern exists or when the emissions abatement efficiencies differ in collaborative entities. Vertically, firms could make production, inventory, and

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Table 3
Carbon-constrained output decision models.

Study	Carbon constraints			Model	Solution approach
	Cap	Tax	ETS		
Zhang and Xu (2013)		√	√	Multi-variable optimization (max expected profit)	Binary-search-based algorithm
Du et al. (2013)			√	Stackelberg game	Analytics
Du, Ma et al. (2015a)			√	Stackelberg game	Analytics
Helmrich et al. (2015)	√			Multi-variable optimization (min cost)	Lagrangian heuristics, FPTAS
He et al. (2015)		√	√	EOQ-based optimization (min cost)	Analytics
Liu et al. (2015)	√	√	√	Single-variable optimization (max expected profit)	Analytics (max–min approach)
Wang and Choi (2015)			√	Single-variable optimization (max shareholder wealth)	Analytics
Wang and Choi (2016)	√		√	Single-variable optimization (max expected profit)	Analytics
Xu, Xu et al. (2016b)		√	√	Stackelberg game	Analytics
Sabzevar et al. (2017)	√		√	Cournot game	Analytics
He et al. (2017)			√	Stackelberg game	Analytics
Meng et al. (2018)		√		Stackelberg game	Analytics
Yuan et al. (2018)			√	Multi-variable optimization (min discounted cost)	Heuristics

Note: FPTAS: fully polynomial time approximation schemes.

delivery decisions jointly to reduce the carbon emissions of the entire chain and share the emissions abatement credits (Caro, Corbett, Tan, & Zuidwijk, 2013). Horizontally, co-opetition could exist when firms in the same industry have different carbon emissions abatement costs (Luo et al., 2016). The firm with the higher emissions abatement cost could transfer part of its emissions reduction target to the more cost-efficient firm and share the cost savings. Collaborative firms may also agree on each other's emissions abatement obligation, technology standards, and other efforts towards low-carbon promotion. Collaborative carbon emissions abatement should be more efficient than internal emissions abatement; however, the challenge of adopting this strategy is designing effective contracts to sustain the collaborative relationship.

3.3. Carbon compensation

If all of the above-mentioned carbon emissions abatement strategies are cost-prohibitive, a firm may adopt the carbon compensation strategy and pay for carbon emissions instead of implementing emissions abatement measures in order to be compliant with the carbon constraints. Under policy-driven carbon constraints, a firm may pay additional taxes for each unit of carbon emissions, purchase certified emissions reduction (CER) credits from a third party, or buy carbon emissions permits from the emissions trading market. Whether a firm can implement the above-mentioned compensation strategies depends on the supporting government policies. Under the market-driven carbon constraints, such as consumer preference for low-carbon footprints and a product's low-carbon competition, a firm could adjust its product price for compensation. By reducing a product's price, the firm sacrifices its marginal profit to compensate for its carbon emissions embodied in the product. Whether a firm should take compensation strategies or emissions abatement strategies depends on the cost-benefit analysis between these available choices.

4. Carbon-constrained operations models

In line with the framework shown in Fig. 1, we collect more than 100 studies published in peer-reviewed international journals mainly in the operations research area, e.g., *European Journal of Operational Research*, *Operations Research*, *Omega* and *Annals of Operations Research*, and provide a sketch of the carbon-constrained operations models. To ensure the quality and consistency of the selected studies, we exclude some publications according to the following guidelines: (1) the publications that do not explicitly focus on carbon-constrained operations decisions, including those study pollution control problems; (2) the studies that focus only on minimizing carbon emissions and not deal with carbon constraints; (3) the publications that focus on the implementation of specific low-carbon technologies such as carbon capture and storage, combined heat and power systems, and renewable energy techniques; and (4) the simulation studies that do not focus on theoretical modeling. After the filtering procedure, 116 papers remain, which are discussed in the following subsections.

4.1. Internal carbon emissions abatement decisions

4.1.1. Output decisions

Table 3 shows the thirteen publications on carbon-constrained output decision models that have been collected (EOQ refers to economic order quantity). These models consider production output adjustment as a compliance strategy towards policy-driven carbon constraints, including carbon emissions caps (either a total cap or unit caps), carbon taxes, and ETS. As discussed earlier, the output reduction strategy is not effective for market-driven carbon constraints, so only the policy-driven carbon constraints have been integrated into the output decision models. Table 3 shows that optimization is the main methodology for studying the carbon-constrained output decision problem, which consists of maximizing profit (e.g., Liu, Holmbom, Segerstedt, & Chen, 2015; Wang & Choi, 2016), minimizing cost (e.g., He, Zhang, Xu, & Bian, 2015), and improving other performance indicators such as shareholder wealth (e.g., Wang & Choi, 2015). If multiple players are involved, game theoretic models could be constructed, either sequentially (e.g., Du, Zhu, Liang, & Ma, 2013; Du, Ma, Fu, Zhu, & Zhang, 2015; He, Dou, & Zhang, 2017; Meng, Yao, Nie, & Zhao, 2018; Xu, Xu, & He, 2016) or simultaneously (e.g., Sabzevar, Enns, Bergerson, & Kettunen, 2017), depending on the situations studied. In addition to single-product and single-period output decision models, multi-product (e.g., Xu, Xu et al., 2016; Zhang & Xu, 2013) and multi-period (e.g., He et al., 2015; Helmrich, Jans, van den Heuvel, & Wagelmans, 2015; Wang & Choi, 2016; Yuan, Chen, Yang, & Zhou, 2018) production planning problems have been studied. In Yuan et al. (2018), the emissions permit trading decision for each period is also explored while the transaction costs are involved. The optimization problems could be $\mathcal{NP}$-hard if multiple constraints or factors are considered. In these situations, effective algorithms are essential for solving the problems (Helmrich et al., 2015).

4.1.2. Product improvement decisions

The existing carbon-constrained operations models concerning product improvement can be categorized into two types: product portfolio design and emissions abatement investment. Table 4 shows carbon-constrained product portfolio decision models from thirteen publications. These models aim to make decisions on

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Table 4
Carbon-constrained product portfolio decision models.

Study	Carbon constraints			Model	Solution approach
	Cap	Tax	ETS		
Gong and Zhou (2013)			√	Multi-variable optimization (min discounted cost)	Heuristics
Chang et al. (2015)			√	Three-variable optimization (max profit)	Analytics
Chen, Chan et al. (2016a)	√		√	Two-variable optimization (max expected profit)	Analytics
Drake et al. (2016)		√	√	2-stage optimization (max expected profit)	Analytics
Hong et al. (2016)	√		√	Multi-variable optimization (min cost)	PDP algorithm
Yenipazarli (2016)		√	√	Stackelberg game	Analytics
Chang et al. (2017)			√	Three-variable optimization (max profit)	Analytics
García-Alvarado et al. (2017)	√		√	Multi-variable optimization (min cost)	Dynamic programming run by Matlab
Hong et al. (2017)			√	Stackelberg game	Hybrid algorithm[a]
Shu et al. (2017)			√	EOQ-based optimization (min cost)	Analytics
Song et al. (2017)		√	√	2-stage optimization (max expected profit)	Analytics
Wang, Chen et al. (2017b)			√	Two-variable optimization (max expected profit)	Analytics
Wang, Zhu et al. (2018b)		√		Three-variable optimization (max profit)	Analytics

Note: PDP: polynomial time dynamic programming.
[a] This hybrid algorithm consists of polynomial time dynamic programming, binary search, and genetic algorithm.

Table 5
Carbon-constrained emissions abatement decision models.

Study	Carbon constraints				Model	Abatement cost function
	Tax	ETS	Offset	LC-demand		
Wang and Wang (2015)		√	√		Cournot game	Quadratic in total reduction
Du, Hu et al. (2016a)		√		√	2-stage optimization	Unlimited
Wang, Liu et al. (2016a)	√				2-stage games	Quadratic in unit abatement
Cao et al. (2017)		√		√	Stackelberg game	Quadratic in unit abatement
Chen et al. (2017)				√	Stackelberg game	Quadratic in unit abatement
Du et al. (2018)		√			Stackelberg game	Fixed + linear variable
Wang, Wan et al. (2018a)		√			Two-variable optimization (max expected profit)	Linear in total reduction
Wen et al. (2018)		√		√	2-stage games	Quadratic in unit abatement

mixed production quantities by different technologies or processes. Some models explore the joint production decisions by traditional technology and low-carbon technology that usually has higher production cost and lower emissions intensity (e.g., Chen, Chan, & Lee, 2016; Drake et al., 2016; Gong & Zhou, 2013; Hong, Chu, & Yu, 2016, 2017; Song, Govindan, Xu, Du, & Qiao, 2017), while other models explore the production decisions through manufacturing and remanufacturing processes (e.g., Chang, Xia, Zhu, Fan, & Zhao, 2015, 2017; García-Alvarado, Paquet, Chaabane, & Amodeo, 2017; Shu et al., 2017; Wang, Chen, & Liu, 2017; Wang, Zhu, Sun, & Jia, 2018; Yenipazarli, 2016). Similar to the output decision models, optimization has been the dominant method for studying the product portfolio decision problem and policy-driven carbon constraints have been considered more frequently. Several other considerations have been incorporated into these models, including emissions trading decisions (Gong & Zhou, 2013), capacity decisions (Drake et al., 2016; Song et al., 2017), carbon permits allocation effects (Chang, Li, Zhao, Liu, & Wu, 2017), and capital constraints (Wang, Chen et al., 2017). However, the market-driven carbon constraints, such as the consumer low-carbon preference, have only appeared in the discussion part of Wang, Zhu et al. (2018). As product portfolio design often leads to product dfferentiation that may affect market shares in practice, thus more studies of the market factors in the product portfolio decision models are suggested.

Table 5 presents eight studies on carbon emissions abatement decision models (LC-demand refers to consumer preference towards low-carbon products). These studies consider a firm's direct investment in carbon emissions abatement (counted as either total emissions quantity or unit emissions intensity). In addition to the policy-driven carbon constraints, consumer preference has been incorporated into the models by adding linear terms to the demand functions. See, for example, Cao, Xu, Wu, and Zhang (2017), Chen et al. (2017), Wen, Zhou, and Zhang (2018), and Du, Hu, and Song (2016). Market competition in a product's low-carbon quality and price/quantity has also been considered, e.g., Wang and Wang (2015), Wang, Liu, Chan, Choi, and Yue (2016) and Wen et al. (2018). In addition, the government's low-carbon production subsidy has been taken into consideration (Cao et al., 2017). A primary modeling issue in this category is the construction of the emissions abatement cost function. The most commonly used functional format is quadratic in total emissions reduction or unit emissions abatement, which captures the increasing marginal cost of carbon emissions abatement (Cao et al., 2017; Chen et al., 2017; Wang & Wang, 2015; Wang, Liu et al., 2016; Wen et al., 2018). In some models, the linear functions are also adopted for convenience of exposition (Du, Zhu, Zhu, & Tang, 2018; Wang, Wan, Li, Luo, & Wang, 2018). In addition, Du, Hu et al. (2016) use unlimited emissions abatement cost functions and discuss the effects of different emissions abatement cost efficiencies. In order to capture more realistic aspects, practical modeling techniques besides the linear and quadratic formats remain to be further developed.

4.1.3. Process improvement decisions

By adopting a process improvement strategy, firms aim to abate indirect carbon emissions associated with the final products, which may be generated in single or multiple stages of the supply chain, including procurement, inventory, and distribution. Table 6 shows nine publications that focus on carbon-constrained procurement models involving procurement sources and quantities decisions. Some publications study the joint decision of supplier selection and order quantities with multiple suppliers through mixed integer linear programming (MILP) models (e.g., Absi, Dauzère-Pérès, Kedad-Sidhoum, Penz, & Rapine, 2013, 2016; Palak, Ekşioğlu, & Geunes, 2014), while some other studies model

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Table 6
Carbon-constrained procurement decision models.

Study	Carbon constraints				Model	Solution approach
	Cap	Tax	ETS	Offset		
Absi et al. (2013)	√				MILP (min cost)	Dynamic programming algorithm
Rosič and Jammernegg (2013)		√	√		Two-variable optimization (max expected profit)	Analytics
Choi (2013a)		√			2-stage optimization (max expected profit)	Dynamic programming algorithm
Choi (2013b)		√			Two-variable optimization (max expected profit)	Analytics
Arıkan and Jammernegg (2014)	√				Single-variable optimization (max expected profit)	Analytics
Palak et al. (2014)	√	√	√	√	MILP (min cost)	ILOG/CPLEX commercial solver
Absi et al. (2016)	√				MILP (min cost)	Dynamic programming algorithm
Sunar and Plambeck (2016)		√			Stackelberg game	Analytics
Ma et al. (2018)		√			2-stage optimization (min discounted cost)	Dynamic programming algorithm

Table 7
Carbon-constrained inventory management models.

Study	Carbon constraints				Model	Demand
	Cap	Tax	ETS	Offset		
Hua et al. (2011)			√		EOQ-based optimization (min cost)	Constant rate
Benjaafar et al. (2013)	√	√	√	√	MILP (min cost)	Time- dependent
Chen et al. (2013)	√	√	√	√	EOQ-based optimization (min cost)	Constant rate
Toptal et al. (2014)	√	√	√		EOQ-based optimization (min cost)	Constant rate
Dye and Yang (2015)			√	√	Three-variable optimization (max expected profit)	Credit period dependent
Hovelaque and Bironneau (2015)		√	√		EOQ-based optimization (max profit)	Linear in price and emissions
Tang et al. (2015)	√				Two-variable optimization (min daily average cost)	Stochastic
Chen, Wang et al. (2016b)			√		Single/two-variable optimization (max expected profit)	Stochastic
Purohit et al. (2016)			√		MILP (min expected cost)	Stochastic
Tang et al. (2018)	√	√		√	Two-variable optimization (min per time unit cost)	Stochastic

supplier selection and order quantity decisions into two-stage optimization problems (e.g., Choi, 2013a; Ma, Ji, Ho, & Yang, 2018). As a longer distance usually leads to more carbon emissions during transportation, distance has been a primary factor when considering carbon-constrained supplier selection; therefore, offshore vs onshore sourcing problems have come into the spotlight (Arıkan & Jammernegg, 2014; Choi, 2013b; Rosič & Jammernegg, 2013). In this category, carbon tax has been the dominant carbon constraint studied, which implies that emissions cost may be the primary carbon driver for firms to change procurement decisions. In addition, Sunar and Plambeck (2016) explore the sequential decisions of multiple buyers in the emissions regulated region and one supplier from the non-regulated region when the border adjustment emissions tax exists.

Table 7 focuses on inventory management aspects and summarizes ten articles on carbon-constrained inventory models. In this category, Benjaafar et al. (2013) build an illustrative framework for integrating carbon constraints into lot-sizing decision models. They also extend single-firm models to multi-firm cases and discuss collaboration effects. Early publications in this category mainly model constant demand rate and make extensions based on the EOQ model (e.g., Chen, Benjaafar, & Elomri, 2013; Hua, Cheng, & Wang, 2011; Toptal, Özlü, & Konur, 2014). Recently, the research focus has shifted to study stochastic demand (e.g., Chen, Wang, Kumar, & Kumar, 2016; Purohit et al., 2016; Tang, Wang, Yan, & Hao, 2015, 2018) and to consider more influential factors such as credit period (Dye & Yang, 2015) and retail price (Hovelaque & Bironneau, 2015). In addition to order quantity decisions, inventory decisions such as order interval, order-up-to level, and order-trigger inventory point have been studied (Tang et al., 2015). To enrich the model settings, some studies have incorporated additional discussions on the impacts of emissions reduction investments (Toptal et al., 2014), perishable goods (Dye & Yang, 2015), and service level constraints (Purohit, Shankar, Dey, & Choudhary, 2016).

Table 8 shows eleven publications that focus on carbon-constrained logistics planning models (MINLP refers to mixed integer non-linear programming). In this category, Hoen, Tan, Fransoo, and van Houtum (2014) set an example for studying the carbon-constrained transportation mode selection problems. Afterward, some scholars study carbon-constrained order quantity and transportation mode decisions jointly from the buyer's perspective (e.g., Chen & Wang, 2016; Hariga, As'ad, & Shamayleh, 2017; Konur, 2014; Konur & Schaefer, 2014); while some other scholars model carbon-constrained vehicle routing problems from the distributor's perspective (e.g., Jin, Granda-Marulanda, & Down, 2014; Li, 2015; Zhang, Zhao, Xue, & Li, 2015). Further, some studies explore joint production/inventory routing problems with carbon constraints (e.g., Cheng, Qi, Wang, & Zhang, 2016; Li, Su, & Ma, 2017; Qiu et al., 2017). In addition to the carbon constraints and traditional factors considered in the distribution problems, Li (2015) take price discount into the manufacturer's consideration, and Hariga et al. (2017) incorporate characteristics of the cold supply chain. Some of the models are $\mathcal{NP}$-hard and thus effective algorithms have been developed (e.g., Cheng et al., 2016; Qiu, Qiao, & Pardalos, 2017; Zhang et al., 2015).

Table 9 shows twenty-five publications that model carbon-constrained supply chain network design problems. Some studies focus on facility location decisions and corresponding configuration in the retailing network (e.g., Cachon, 2014; Dilek, Karaer, & Nadar, 2018; Ghaddar & Naoum-Sawaya, 2012; Park, Cachon, Lai, & Seshadri, 2015); some studies focus on the material flow and configuration design within the supply chain network (e.g., Elhedhli & Merrick, 2012; Hammami, Nouira, & Frein, 2015; Hong, Dai, Luh, & Yang, 2018; Huang, Wang, Zhang, & Pang, 2016; Liotta et al., 2015); while some other studies try to cover a wider range of the supply chain network design problems including capacity decisions (e.g., Rezaee, Dehghanian, Fahimnia, & Beamon, 2017; Turken et al., 2017), procurement decisions (e.g., Brandenburg, 2015; Wu, Jin, Shi, & Shyu, 2017), production decisions (e.g., Fahimnia, Sarkis, Choudhary, & Eshragh, 2015; Rahmani & Mahoodian, 2017; Zakeri et al., 2015), and inventory decisions (e.g., Diabat & Al-Salem, 2015; Martí et al., 2015). In addition to forward supply

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Table 8
Carbon-constrained logistics planning models.

Study	Carbon constraints				Model	Solution approach
	Cap	Tax	ETS	Others		
Hoen et al. (2014)	√	√	√		Single-variable optimization (min expected cost)	Analytics
Konur (2014)	√				MINLP (min cost)	Search heuristic
Konur and Schaefer (2014)	√	√	√	Offset	EOQ-based optimization (min cost)	Analytics
Jin et al. (2014)	√	√	√		MILP (min cost)	Commercial solver
Li (2015)		√			MINLP (max profit)	Greedy algorithm
Zhang et al. (2015)		√			MILP (min cost)	RS-TS algorithm
Chen and Wang (2016)	√		√		Two-variable optimization (max expected profit)	Analytics
Cheng et al. (2016)	√	√	√	Offset	MINLP (min cost)	Hybrid genetic algorithm
Hariga et al. (2017)		√			MINLP (min cost)	Iterative search algorithm
Li et al. (2017)		√	√		2-stage Optimization	Analytics
Qiu et al. (2017)			√		MILP (min cost)	Branch-and-price algorithm

Note: S-TS: route splitting tabu search.

Table 9
Carbon-constrained supply chain network design models.

Study	Carbon constraints				Model and solution approach	Decisions						
	Cap	Tax	ETS	Others		L	C	Pc	Pd	I	D	R
Chaabane et al. (2012)			√		Multi-objective MILP and LINGO solver	√		√	√	√	√	√
Elhedhli and Merrick (2012)				Carbon cost	MINLP and Lagrangian heuristic	√					√	
Ghaddar and Naoum-Sawaya (2012)			√		MINLP and LindoGlobal solver	√					√	
Fahimnia et al. (2013)		√			MILP and CPLEX solver	√			√	√	√	√
Cachon (2014)				Carbon cost	Two-stage optimization and analytics	√	√				√	
Brandenburg (2015)				Carbon cost	Multi-objective MILP and CPLEX solver	√		√	√	√	√	
Choudhary et al. (2015)	√	√	√		MINLP and forest-data-structure algorithm	√					√	√
Diabat and Al-Salem (2015)			√		MINLP and genetic algorithm	√				√	√	
Fahimnia et al. (2015)		√			MINLP and cross-entropy algorithm	√			√	√	√	
Hammami et al. (2015)	√	√			MINLP and CPLEX solver			√	√	√	√	
Liotta et al. (2015)		√			MILP and CPLEX solver	√		√	√		√	
Martí et al. (2015)	√	√			MILP and CPLEX solver	√				√	√	
Park et al. (2015)		√			Three-stage optimization and analytics	√	√				√	
Zakeri et al. (2015)		√	√		MILP and CPLEX solver	√			√	√	√	
Huang et al. (2016)				Carbon cost	Stakelberg game and genetic algorithm			√	√		√	
Nouira et al. (2016)				LC- demand	MINLP and CPLEX solver	√		√	√		√	
Mohammed et al. (2017)	√	√	√	Offset	MILP and CPLEX solver	√		√	√	√	√	√
Rahmani and Mahoodian (2017)	√				MILP and CPLEX solver/benders-decomposition algorithm	√			√		√	
Rezaee et al. (2017)			√		MINLP and CPLEX solver	√	√	√	√		√	
Turken et al. (2017)	√	√			MINLP and linear- approximation algorithm	√	√		√		√	
Wu et al. (2017)				Carbon cost	Two-stage optimization and analytics	√		√				
Xu, Pokharel et al. (2017)	√	√	√		MILP and CPLEX solver	√		√			√	√
Haddadsisakht and Ryan (2018)		√			MINLP and benders- decomposition algorithm	√					√	√
Dilek et al. (2018)		√			Two-variable optimization and analytics	√						
Hong et al. (2018)	√			Subsi-dy	MINLP and STA+PSO			√	√	√	√	

Note: L: Location; C: Capacity; Pc: Procurement; Pd: Production; I: Inventory; D: Distribution; R: Recycling; STA: spanning tree-based algorithm; PSO: particle swarm optimization algorithm.

chains, some scholars incorporate reverse supply chains and recycling decisions into their models (e.g., Chaabane, Ramudhin, & Paquet, 2012; Choudhary, Sarkar, Settur, & Tiwari, 2015; Fahimnia, Sarkis, Dehghanian, Banihashemi, & Rahman, 2013; Mohammed, Selim, Hassan, & Syed, 2017; Xu, Pokharel, Elomri, & Mutlu, 2017). The dominant carbon constraints considered in this category are also policy-driven constraints, while Nouira, Hammami, Frein, and Temponi (2016) set an example for modeling supply chain network design problems with carbon-sensitive demand. Moreover, some scholars incorporate carbon price uncertainty in their models (Haddadsisakht & Ryan, 2018; Rezaee et al., 2017). One important aspect for studying carbon-constrained supply chain network design problems is to choose an appropriate optimization solution method because the constructed models are often large and complicated. As shown in the table, most MILP models could be solved by commercial solvers such as LINGO and CPLEX, while MINLP models often require effective algorithms to be developed.

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Table 10
Carbon-constrained collaborative emissions abatement models.

Study	Carbon constraints				Player	Decision	Collaborating way
	Cap	Tax	ETS	LC-demand			
Caro et al. (2013)		√			1 social planner 1 SC leader *n* SC followers	Footprint allocation Abatement effort, cost share Abatement effort	Cost-sharing
Jaber et al. (2013)		√	√		1 vendor 1 buyer	Production rate Shipments	Joint decisions
Zanoni et al. (2014)			√		1 vendor 1 buyer	Production rate Shipments	Joint decisions
Du, Zhu et al. (2015b)				√	1 manufacturer 1 retailer	Abatement effort, wholesale price Retail price	Wholesale-price, revenue-sharing, Volume-discount
Dong et al. (2016)			√	√	1 manufacturer 1 retailer	Abatement effort Order quantity	Revenue-sharing, Buyback, Two-part tariff
Ding et al. (2016)			√		1 manufacturer 1 supplier	Production quantity Sales quantity	Subsidy-sharing
Luo et al. (2016)			√	√	2 manufacturers	Abatement efforts, Product prices	Co-opetition
Wang, Zhao et al. (2016b)			√		1 manufacturer 1 retailer	Abatement effort Order quantity	Wholesale-price, Cost-sharing
Xu, Chen et al. (2016a)			√	√	1 manufacturer 1 supplier	Abatement effort, selling price Wholesale price	Revenue-sharing, two-part tariff
Zhou et al. (2016)				√	1 manufacturer 1 retailer	Abatement effort Advertising effort	Cost-sharing, Co-op advertising
Du et al. (2017)				√	1 manufacturer 1 retailer	Abatement effort, wholesale price Abatement effort, retail price	Linear price- discount sharing
Ji et al. (2017a)			√	√	1 manufacturer 1 retailer	Abatement effort, wholesale price Promotion effort, retail price	Abatement +promotion
Ji et al. (2017b)			√	√	1 manufacturer 1 retailer	Abatement effort, wholesale price Promotion effort, retail price	Joint reduction +promotion
Konur (2017)	√				1 leader 1 follower	Lot-size quantity individual decisions Individual decisions	Joint target with leadership
Toptal and Çe-tinkaya (2017)		√	√		1 vendor 1 buyer	Lot-size quantity	Carbon credit sharing
Wang, Wang et al. (2017a)		√			1 government 1 manufacturer 1 retailer	Carbon tax Wholesale price Order quantity	Centralized decisions
Xu, He et al. (2017a)			√	√	1 manufacturer 1 retailer	Abatement effort, wholesale price Order quantity	Wholesale-price, cost-sharing
Yang, Luo et al. (2017a)			√	√	1 manufacturer 1 retailer	Abatement effort, Order quantity	Wholesale-price, Revenue-sharing
Yang, Zhang et al. (2017b)			√	√	2 manufacturers 2 retailers	Abatement efforts, wholesale prices Retail prices	Co-opetition, revenue-sharing
Chen et al. (2018)		√			1 buyer 1 supplier	Order quantity Order frequency	Shared emissions responsibility
Xia et al. (2018)			√	√	1 manufacturer 1 retailer	Abatement effort, wholesale price Retail price	Centralized decisions
Yang and Chen (2018)		√		√	1 manufacturer 1 retailer	Abatement effort, wholesale price Order quantity	Revenue-sharing, cost-sharing

4.2. Collaborative carbon emissions abatement decisions

In the collaborative carbon emissions abatement modeling literature, most studies consider vertical coordination within supply chains (as shown in Table 10). Some scholars model carbon-constrained supply chain coordination from a centralized perspective, e.g. Jaber, Glock, and El Saadany (2013), Wang, Wang, and Huang (2017a), Xia, Guo, Qin, Yue, and Zhu (2018), and Zanoni, Mazzoldi, and Jaber (2014), while some other scholars design contracts for achieving the coordinated outcomes. The employed contracts include cost-sharing contract (Caro et al., 2013; Wang, Zhao, & He, 2016; Xu, He, Xu, & Zhang, 2017; Yang & Chen, 2018; Zhou et al., 2016), wholesale price contract (Du, Zhu, Jiao, & Ye, 2015; Wang, Zhao et al., 2016; Xu, He et al., 2017; Yang, Luo, & Wang, 2017), revenue-sharing contract (Dong, Shen, Chow, Yang, & To Ng, 2016; Du, Zhu et al., 2015; Xu, Chen, & Bai, 2016; Yang & Chen, 2018; Yang, Luo et al., 2016), quantity-discount contract (Du, Zhu et al., 2015), buyback contract (Dong et al., 2016), two-part tariff contract (Dong et al., 2016; Xu, Chen et al., 2016), subsidy sharing contract (Ding, Zhao, An, & Tang, 2016), carbon emissions responsibility/credit sharing contract (Chen, Benjaafar, & Elomri, 2018; Konur, 2017; Toptal & Çetinkaya, 2017), and linear price-discount sharing contract (Du, Hu, & Wang, 2017). The main purpose of these contracts is to design mechanisms that enable supply chain partners to undertake emissions abatement jointly and share the abatement costs or potential gains. In addition to emissions abatement considerations, Zhou, Bao, Chen, and Xu (2016), and Ji, Zhang, and Yang (2017a, 2017b) have incorporated the low-carbon advertising or promotion efforts of retailers. The reciprocal preference and fairness perception have also been modeled (Xia et al., 2018). In addition to vertical coordination, two listed publications model horizontal co-opetition problems. In Luo, Chen, and Wang (2016), they consider two manufacturers competing in both product price and low-carbon quality and analyze the co-opetition by maximizing the sum of the competitors' profits. In Yang, Zhang, and Ji (2017), they consider both vertical coordination and horizontal co-opetition in a system with two manufacturers and two retailers.

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Table 11
Carbon-constrained pricing decision models.

Study	Carbon constraints			Player	Decision	Model
	Tax	ETS	LC-demand			
Chen and Hao (2015)	√			2 manufacturers	Retail prices	Competition game
Du, Tang et al. (2016b)		√	√	1 manufacturer	Prices for 2 products (low-carbon vs ordinary)	Dual-variable optimization
Xu, Zhang et al. (2017b)		√		1 manufacturer 1 retailer	Prices for 2 products (low-carbon vs ordinary) Order quantities	Stackelberg Game
Miao et al. (2018)	√	√		1 manufacturer	Prices for 2 products (new vs remanufactured), trade-in rebate	Triple-variable optimization
Ding et al. (2018)	√		√	2 retailers	Prices, service times	Competition game

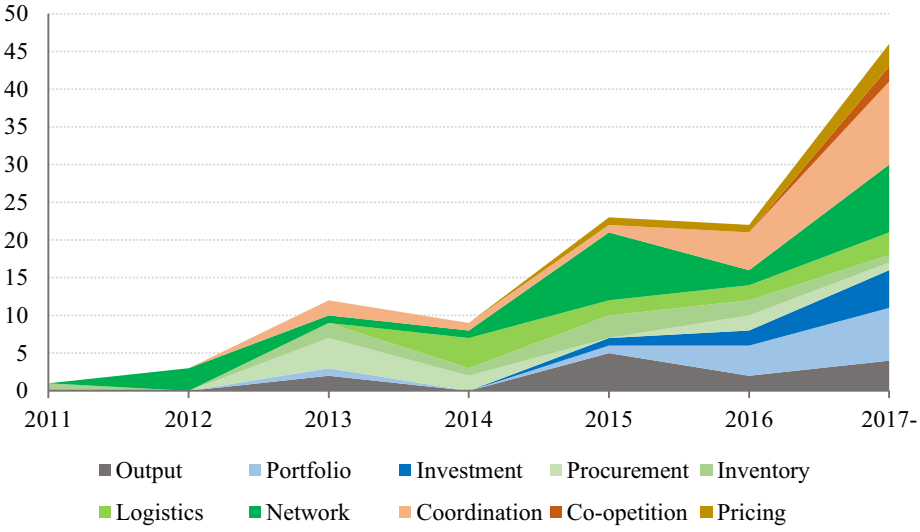

Fig. 2. Publication trend on carbon-constrained operations models over time. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

4.3. Carbon compensation decisions

Most of the collected operations models treat carbon compensation decisions as indirect decisions. Once the above-mentioned operations decisions have been made, the consequential carbon emissions will be identified and the firms' carbon compensation decisions (such as the purchasing carbon credit quantities and the underlying penalties) will be derived. However, one type of carbon compensation strategy has been modeled independently, that is, adjusting product price. By reducing product price, a firm could compensate for consumers aversion towards carbon emissions that embedded in the product; while on the contrary, by enhancing product price, a firm could transfer part of its emissions cost and abatement cost (if any) to consumers. In addition, pricing competition is quite common in practice for firms to cope with competitive situations. Table 11 lists five publications that focus on this type of carbon compensation decisions. Some scholars model pricing decisions for different types of products (i.e., low-carbon vs ordinary products, or remanufactured vs new products) from a single manufacturer's perspective (e.g., Du, Tang, & Song, 2016; Miao, Mao, Fu, & Wang, 2018; Xu, Zhang, He, & Xu, 2017), while some other scholars study pricing competition games (e.g., Chen & Hao, 2015; Ding, Gao, Huang, Shu, & Yang, 2018). In Miao et al. (2018), the trade-in rebate is also considered. In Ding et al. (2018), the service time competition is also studied.

5. Main findings from previous studies

5.1. Developing trend with respect to different business strategies

The developing trend of carbon-constrained operations modeling literature is shown in Fig. 2. The number of related publications has increased fast since 2011, while the burst in 2015 may be due to the release of two special issues by two academic journals (IJPE and JCP). By looking into each category, the internal carbon emissions abatement strategies (gray, blue, and green regions) have been explored much more than the collaborative carbon emissions abatement strategies (orange regions), while the literature on collaborative abatement strategies has increased more rapidly in the last two years. Within the internal carbon emissions abatement category, the process improvement strategies (green regions) have attracted more attention than the product improvement strategies (blue regions), while the output reduction strategy has received the least attention (gray region). The product portfolio design (light blue region) has earned more attention than the abatement investment (dark blue region) in recent years, while the focus of process improvements studies changed from single-stage problems (light green regions) to the network designs (dark green region). Within the collaborative carbon emissions abatement category, the study focus has been on vertical coordination among supply chain partners, while studies regarding horizontal co-opetition have been emerging.

A notable fact is that most of these modeling studies are motivated by practical problems. Within the collected 116 carbon-constrained operations modeling papers, 21 of them apply the constructed model to real cases, 87 of them use estimated or simulated data as numerical examples, and only 8 of them focus on theoretical study without implementations (as shown in Fig. 3). This implies that the modeling study trend may reflect the practitioners' concerns to some extent. Combining with the previous analyzed modeling study trend, we may infer that profitable emissions abatement strategies, such as process improvement, which do not harm or cause less harm to the economic aspects, are more preferable to practitioners. Meanwhile, entrepreneurs

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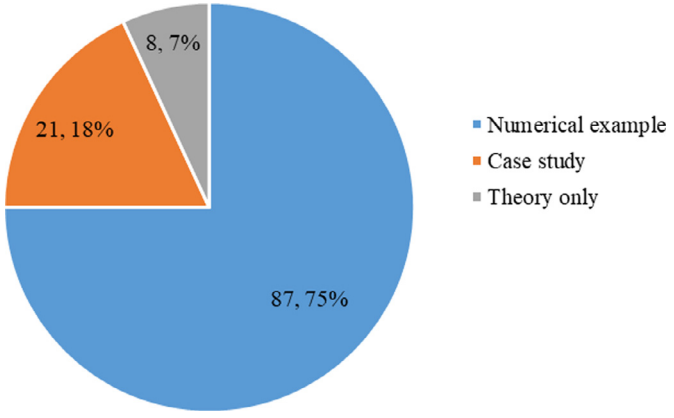

Fig. 3. Division of studies according to model application.

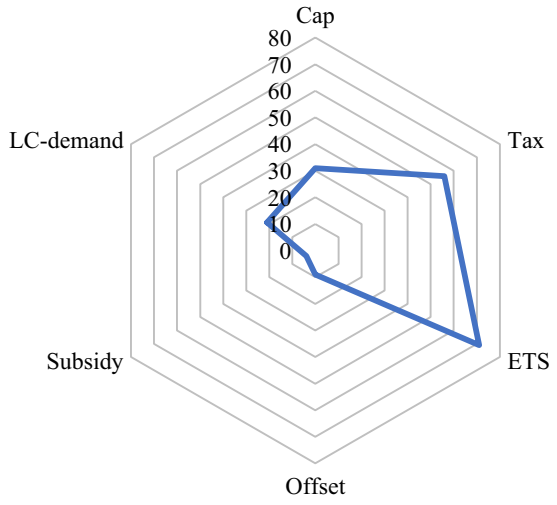

Fig. 4. Overview of modeled carbon constraints.

may be changing their positions on carbon-constrained business strategies from short-term plans such as single-process adjustments to long-term plans such as network designs. In addition, vertical coordination seems to have attracted growing attention because such strategy could achieve emissions abatement targets with relatively low cost and that cooperation among supply chain partners is relatively easy to establish by applying the appropriate contracts. Although cooperation between competitors is relatively rare in practice at current stage, there are opportunities for competitors to work together and achieve win–win goals in terms of carbon emissions abatement. As such, co-opetitive carbon emissions abatement mechanism needs further study.

5.2. Modeling of carbon constraints

In the carbon-constrained operations modeling literature, the dominant carbon constraints that have been studied are policy-driven constraints, including carbon caps, taxes, ETS, cap-and-offset, and additional subsidies for low-carbon technologies (as shown in Fig. 4). In addition, the market-driven carbon constraint of low-carbon consumer preference has been explored. However, the nature-driven carbon constraints have not been incorporated into the operations models so far. In terms of policy-driven carbon constraints, the ETS has been the most frequently studied, followed by the carbon tax. The reason behind this phenomenon may be that the ETS has been the most extensively employed policy instrument worldwide for controlling carbon emissions. However, the ETS is usually accompanied by other policy instruments such as low-carbon technology subsidies in practice. As such, the examination of the interactive effects of multiple policy instruments would be interesting.

To understand the primary carbon constraints considered in each category of the above-mentioned operations models, we analyze the modeled carbon constraints (shown in Fig. 5). Fig. 5 shows that output reduction and process improvement strategies primarily consider policy-driven carbon constraints, while low-carbon demand has been considered mainly in product improvement and collaborative emissions abatement strategies. This implies that although policy-driven carbon constraints may be the primary driving force for firms' emissions abatement activities, the market-driven carbon constraints, such as low-carbon demand, have been an important factor for firms to adopt product improvement and collaborative emissions abatement strategies. While the ETS has been the dominant carbon constraint studied in most categories, the carbon tax exceeds the ETS in most of the process improvement decision categories. This implies that carbon emissions cost may be the dominant factor for firms to choose process improvement strategies.

In the existing studies, policy-driven carbon constraints are usually modeled in the following ways: the carbon cap is modeled by adding an additional emissions constraint function; the carbon tax is modeled by adding an emissions cost to the total cost function; the ETS is modeled by adding both an emissions trading payoff to the objective function and an emissions cap condition to the constraint set; the cap-and-offset policy is modeled by adding both an emissions offsetting cost to the objective function and an emissions cap condition to the constraint set; and the low-carbon subsidy is modeled by adding an additional gain to the objective function. The market-driven carbon constraint of low-carbon demand is usually modeled by a carbon-sensitive demand function. A frequently used low-carbon demand expression is a linear function that decreases with the carbon emissions intensity of the product. Some other forms such as the exponential demand function and consumers' low-carbon utility distribution have also been applied in the literature. To capture more essential factors in the real world (such as policy uncertainty, market power, human perception bias, etc.), more realistic formulations of the carbon constraints remain to be developed.

5.3. Analyzing framework and methodologies

According to our literature review, optimization has been the dominant methodology for studying carbon-constrained operations decision problems. When a single decision-maker is considered, the optimization models could be constructed with the single objective to maximize profit or minimize cost; with multi-objectives the model could be constructed to achieve economic and carbon management goals simultaneously. A set of constraint functions are needed to fulfill the essential conditions. For instance, the well-known EOQ model is frequently used for studying carbon-constrained inventory problems, while the MILP and the MINLP are frequently applied to carbon-constrained supply chain network design problems. After formulating the optimization problems, three main methods have been applied to solve the models (analytics, algorithms, and computational software). For analytical solvable problems, the analytical results may be derived directly from the formulas by utilizing optimization theories. For the $\mathcal{NP}$-hard problems that are not analytically solvable, scholars have developed various types of computational algorithms such as the heuristic and the genetic algorithms. In addition, computational software

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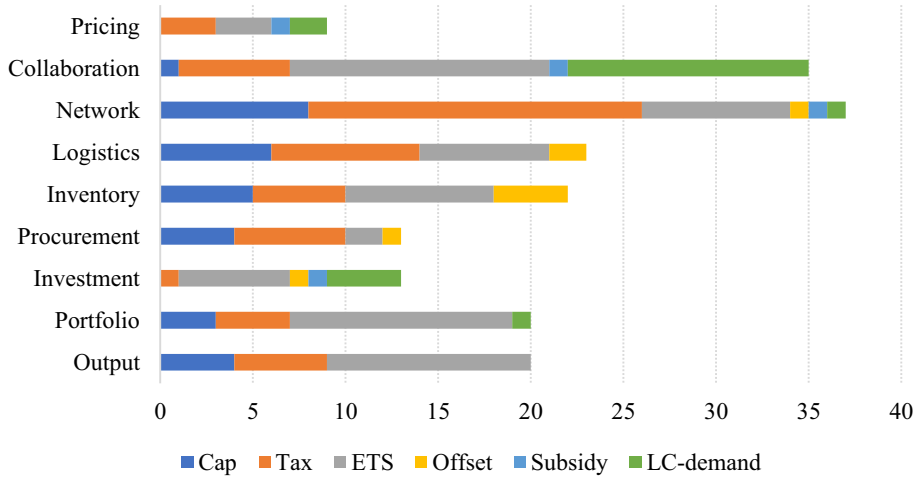

Fig. 5. Breakdown of modeled carbon constraints.

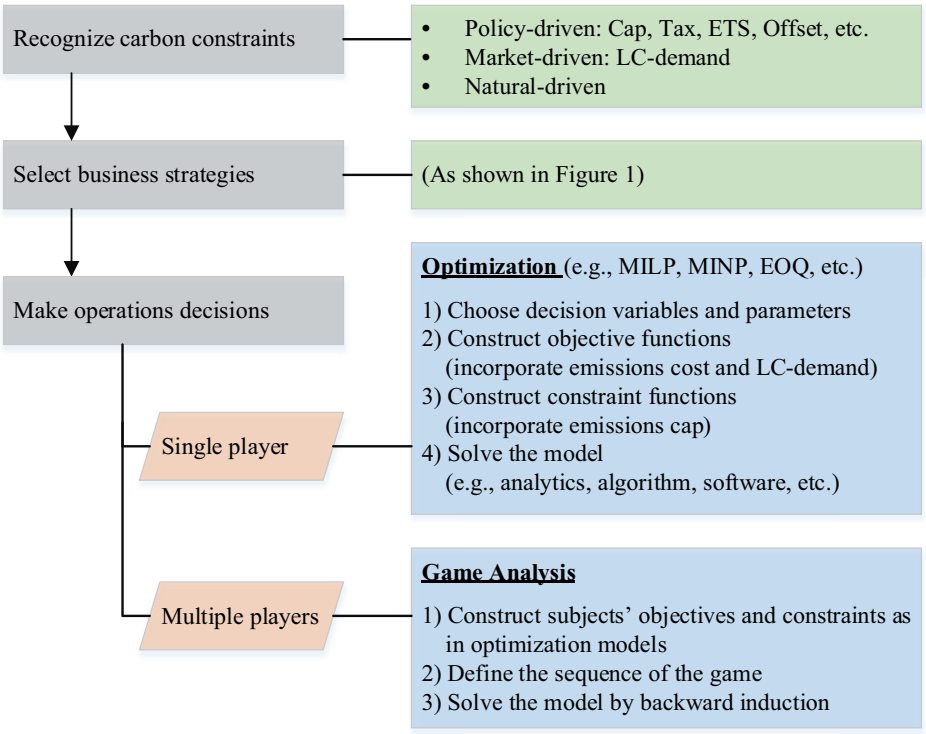
Recognize carbon constraints
• Policy-driven: Cap, Tax, ETS, Offset, etc.
• Market-driven: LC-demand
• Natural-driven
Select business strategies
(As shown in Figure 1)
Make operations decisions
Optimization (e.g., MILP, MINP, EOQ, etc.)
1) Choose decision variables and parameters
2) Construct objective functions
(incorporate emissions cost and LC-demand)
3) Construct constraint functions
(incorporate emissions cap)
4) Solve the model
(e.g., analytics, algorithm, software, etc.)
Single player
Multiple players
Game Analysis
1) Construct subjects' objectives and constraints as in optimization models
2) Define the sequence of the game
3) Solve the model by backward induction

Fig. 6. Analyzing framework for carbon-constrained firm decisions.

such as LINGO, CPLEX, and MATLAB has been used to solve large optimization problems with numerical data. When multiple players are considered, game theoretic models can be established. The payoff function and constraint conditions for each player could be constructed in a similar manner to single-player optimization problems, while each game player should also incorporate other players' impacts into his decision model. If each game player possesses equal power, then the game should be played simultaneously; if any player has greater power and acts as the leader, then the game should be played sequentially. The game models are usually solved by the combination of backward induction and optimization techniques. Fig. 6 shows the conceptual analyzing framework for making carbon-constrained firm decisions, which includes recognizing carbon constraints, selecting business strategies, modeling and making operations decisions.

6. Conclusions

This paper provides a systematic review of carbon-constrained operations modeling studies. First, three genres of carbon constraints are recognized: policy-driven, market-driven, and nature-driven. Second, firms' business strategies for fulfilling the carbon constraints are classified into three main categories: internal emissions abatement, collaborative emissions abatement, and carbon compensation strategies. Third, 116 journal articles on ten specific types of operations models under the three carbon-constrained business strategies are reviewed, which include output decision, product portfolio design, low-carbon investment, procurement decision, inventory control, logistics plan, network design, vertical coordination, horizontal co-opetition, and pricing models. Finally, on the basis of the above reviews, the trends in studying

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carbon-constrained operations models are analyzed, the modeling methodologies are summarized, and a conceptual analyzing framework is proposed for both carbon-concerned practitioners and scholars in the low-carbon operations management area.

By examining the developing trend of the carbon-constrained operations models, three evolving directions are observed: (1) from short-term strategies, such as output reduction, to long-term strategies, such as network design; (2) from internal emissions abatement strategies to collaborative emissions abatement strategies; and (3) from simple models, such as single-product problems, to more practical models, such as mixed-product problems. From the carbon constraint modeling aspect, the policy-driven carbon constraints have been the primary carbon constraints considered in operations models, within which the ETS and the carbon tax take the first and second place, respectively. In addition, market-driven carbon constraints, such as consumer preference towards low-carbon products, have been modeled, while the nature-driven carbon constraints have not been incorporated into operations models so far. The modeled carbon constraints imply the primary driving forces for firms' low-carbon business practices. From the methodology aspect, optimization has been the dominant method for studying single-player problems, while game theoretic models have been applied in multi-player problems. For solving the established models, both analytical methods and computational algorithms have been explored, with particular attention on developing effective algorithms for solving large models.

Carbon-concerned business practitioners may manage carbon constraints according to the analyzing framework proposed in Fig. 6, which consists of recognizing carbon constraints, selecting business strategies, quantifying and making operations decisions. Carbon policy-makers may learn how firms make carbon-constrained operations decisions and use the levers of emissions abatement driving forces appropriately. For researchers in the low-carbon operations management area, we indicate several potential extensions for future studies. First, from the carbon constraint perspective, nature-driven carbon constraints remain to be incorporated into firms' decision models. In addition, more realistic formulations of policy-driven and market-driven carbon constraints that capture uncertainty and competition factors are needed for simulating the real world and generating more practical insights. Moreover, it would be interesting to study the coexistence of multiple carbon constraints and their interactive effects. Second, from the emissions abatement strategy perspective, collaborative emissions abatement mechanisms, especially horizontal co-opetition mechanisms, remain to be further explored. Lastly, from the empirical perspective, studies focusing on specific industries or regions and their comparisons would be interesting.

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